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R. A. Savrai, A. V. Makarov, E. S. Gorkunov, N. N. Soboleva, L. Kh. Kogan, I. Yu. Malygina, A. L. Osintseva, and N. A. Davydova

Eddy-Current Testing of Fatigue Degradation upon Contact Fatigue Loading of Gas Powder Laser Clad NiCrBSi–Cr_3C_2 Composite Coating

R. A. Savrai[1, a)], A. V. Makarov[1, 2, 3], E. S. Gorkunov[1], N. N. Soboleva[1, 3], L. Kh. Kogan[2], I. Yu. Malygina[1], A. L. Osintseva[1] and N. A. Davydova[1]

[1]*Institute of Engineering Science, Ural Branch of the Russian Academy of Sciences, 34 Komsomolskaya St., Ekaterinburg, 620049 Russia*
[2]*Miheev Institute of Metal Physics, Ural Branch of the Russian Academy of Sciences, 18 S. Kovalevskaya St., Ekaterinburg, 620990 Russia*
[3]*Ural Federal University, 19 Mira St., Ekaterinburg, 620002 Russia*

[a)]Corresponding author: ras@imach.uran.ru

Abstract. The possibilities of the eddy-current method for testing the fatigue degradation under contact loading of gas powder laser clad NiCrBSi–Cr_3C_2 composite coating with 15 wt.% of Cr_3C_2 additive have been investigated. It is shown that the eddy-current testing of the fatigue degradation under contact loading of the NiCrBSi–15%Cr_3C_2 composite coating can be performed at high excitation frequencies 72-120 kHz of the eddy-current transducer. At that, the dependences of the eddy-current instrument readings on the number of loading cycles have both downward and upward branches, with the boundary between the branches being 3×10^5 cycles in the given loading conditions. This is caused, on the one hand, by cracking, and, on the other hand, by cohesive spalling and compaction of the composite coating, which affect oppositely the material resistivity and, correspondingly, the eddy-current instrument readings. The downward branch can be used to monitor the processes of crack formation and growth, the upward branch – to monitor the degree of cohesive spalling, while taking into account in the testing methodology an ambiguous character of the dependences of the eddy-current instrument readings on the number of loading cycles.

INTRODUCTION

The eddy-current (EC) method is based on the analysis of interaction of the external electromagnetic field with that of the eddy currents induced by the EC transducer in a sample, and is often used for quality control of electrically conducting objects [1]. Our investigations showed the possibility of applying the EC method for testing and evaluating the chemical and phase compositions, hardness, wear resistance and contact endurance of laser-clad coatings of different types, as well as the thicknesses of weakly magnetic NiCrBSi and CoNiCrW coatings, which are formed on steel surfaces using the gas powder laser cladding technique [2]. The use of the EC method for testing the properties of metal alloys with low permeability was also reported in [3]. The electromagnetic EC method can be used well for testing the accumulated deformation and crack formation under cyclic loading of metal materials [4].

Nickel-chromium alloys are widely used for creation of composite coatings on their basis by adding various additives into the powders, for example, TiC, WC, Cr_3C_2, SiC, TaC, Al_2O_3, Fe_2O_3, V_2O_5. These additives can act differently on the ability of a material to resist mechanical contact. Therefore, investigating the contact endurance and testing the fatigue degradation of composite coatings is an important task. Previously, there have been investigated in [5] the possibilities of the EC method for testing the fatigue degradation under contact loading of laser clad NiCrBSi–TiC composite coatings with 15 and 25 wt.% of TiC additives. The aim of this paper is to study the possibilities of the EC method for testing the fatigue degradation under contact loading of gas powder laser clad NiCrBSi–Cr_3C_2 composite coating with 15 wt.% of Cr_3C_2 additive.

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EXPERIMENTAL PROCEDURE

The powder blend of self-fluxing NiCrBSi alloy (in wt.%: 0.48 C, 14.8 Cr, 2.6 Fe, 2.9 Si, 2.1 B, Ni for balance) with the particle size within 40-160 μm and Cr_3C_2 chromium carbide with the particle size within 50-150 μm served as the coating material. The share of the individual powder in the blend was 85 wt.% of NiCrBSi and 15 wt.% of Cr_3C_2. Low-carbon (0.20 wt.% C) steel plate was clad with the powder blend by CO_2 continuous wave laser using a radiation power of 1.4-1.6 kW; a speed of 160-200 mm/min; a powder consumption of 2.9-4.9 g/min; a surface laser spot size of 6×1.5 mm. The powder blend was transported to the cladding zone by an inert gas (argon) at 0.5 atm. To reduce surface stresses, the cladding was performed in two runs by overlaying one layer on another. The clad coating was subjected to mechanical grinding with high-intensity cooling to the coating thickness of 0.7-1.1 mm.

The mechanical testing for contact fatigue was conducted on an Instron 8801 servohydraulic machine using a fixture of unique design (RU Patent No. 162959) according to the pulsing non-impact "sphere-to-surface" contact scheme with the load changed in a periodic (sine) cycle, the steel ball diameter of 12.7 mm, the pre-loading P_0 = 0.1 kN, the maximum load P_{max} = 8.7 kN and the loading frequency f = 35 Hz based on N = 10^6 loading cycles.

The coating structure and the phase composition were examined using a Tescan VEGA II XMU scanning electron microscope (SEM) with X-ray wavelength-dispersive microanalysis, energy-dispersive microanalysis and EBSD analysis systems. X-ray diffraction analysis was made on a Shimadzu XRD-7000 diffractometer with CrK_α radiation. Microhardness was determined by the recovered indentation method on Shimadzu HMV-G21DT microhardness tester at the load of 0.98 N, the loading rate of 40 μm/s, and load holding for 15 s.

The electromagnetic parameters of the laser clad coating were measured on a laboratory EC instrument using a differentially connected attachable transformer transducer with a projecting ferrite pot core [6] at frequencies f = 36, 72, 96, and 120 kHz.

RESULTS AND DISCUSSION

After double layer laser cladding of the powder blend of NiCrBSi alloy with 15 wt.% of Cr_3C_2 additive, a composite coating is formed on the surface of a steel plate, which contains large undissolved primary Cr_3C_2 particles (Fig. 1a). The average surface microhardness of the composite coating is 1080±110 HV 0.1, which substantially exceeds microhardness of the basic NiCrBSi coating (520±10 HV 0.1) and that of the composite coatings with 15 and 25 wt.% of TiC additives (correspondingly, 720±40 and 770±60 HV 0.1) [5].

According to the data of characteristic electron microprobe analysis, X-ray diffraction analysis and EBSD analysis (Fig. 1b, c), the metal base of the coatings is composed by a Ni-based γ-solid solution and a eutectic comprising a γ-phase and a Ni_3B phase. The strengthening phases of the composite coating are $Cr_{23}C_6$ chromium carbide (microhardness is 1000-1150 HV) as well as large inclusions of Cr_3C_2 chromium carbide (microhardness is 1860-2220 HV). The primary Cr_3C_2 particles partially dissolute during laser cladding, which is followed by deviation from stoichiometric composition, formation of the M_3C_2 type complex carbides and a larger amount of secondary $Cr_{23}C_6$ chromium carbides as compared with the basic NiCrBSi coating [5]. Round-shaped flaws are also present in the structure of the NiCrBSi–15%Cr_3C_2 composite coating (Fig. 1d). At that, the flaws located within large carbide particles or on the border of carbides with a metal matrix are not observed. Such flaws are typical of the composite coatings with TiC additives [5].

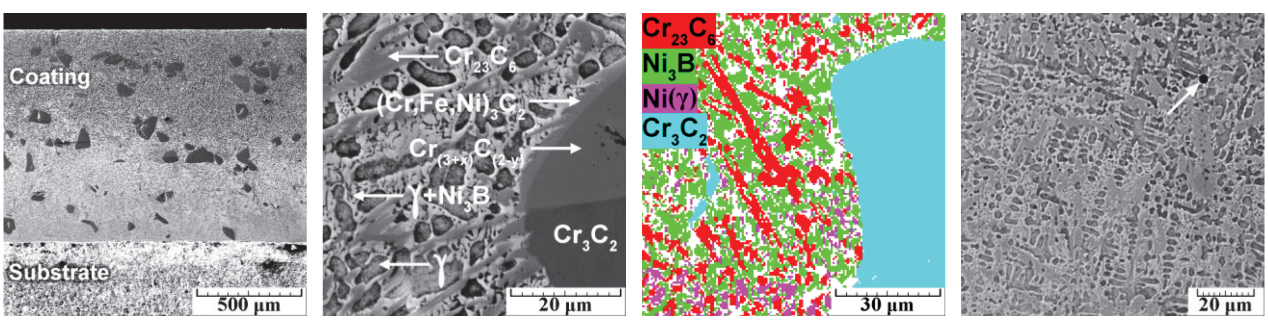
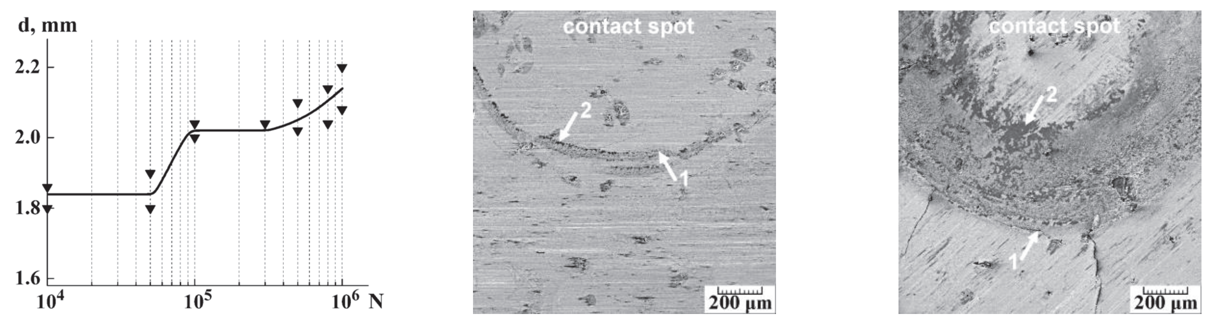


FIGURE 1. General view (a), microstructure (b), EBSD phase map (c) and a flaw (denoted with arrow) in the structure (d) of the NiCrBSi–15%Cr_3C_2 composite coating after laser cladding

The results of contact fatigue tests for the coating under investigation are presented in Fig. 2. From the Fig. 2a, it follows that the contact spot diameter after 10^4 loading cycles on average is 1.83 mm, which is lower than for the basic NiCrBSi coating (2.12 mm) [5]. This is evidently determined by the higher hardness of the NiCrBSi–Cr_3C_2 composite coating in comparison to that of the basic NiCrBSi coanting and, correspondingly, by the enhanced ability of the composite coating to resist plastic deformation under contact fatigue tests. As the number of contact loading cycles grows to 5×10^4, there is no significant change in the contact spot diameter. With the number of contact loading cycles up to 10^5, a sharp increase in the contact spot diameter to 2.00-2.04 mm is observed. The further loading with up to 3×10^5 cycles is again accompanied by the stabilization of the contact spot diameter. As the number of cycles grows from 5×10^5 to 10^6, a continuous increase in the size of contact damages is observed.

The electron microscopy examination of the contact spots (Fig. 2b, c) has shown that cracking and fretting develop in the process of contact fatigue loading of the tested coating. The surface cracking is characterized by the appearance of ring cracks (see Fig. 2b, c, shown by arrows 1) and radial cracks. The ring cracks appearing in the effective zone of maximum radial tensile stresses promote residual stress relaxation within the coating and cohesive failure (coating spalling at the contact spot edge) [5]. For the NiCrBSi–15%Cr_3C_2 composite coating, ring cracking is observed as early as after 10^4 loading cycles. After 5×10^4 cycles, the ring cracks are already fully formed. The further loading is accompanied by cohesive spalling, which causes a sharp increase in the contact spot diameter after 10^5 loading cycles (see Fig. 2a). Fretting wear is described by characteristic dark regions arising near the edges of the contact spots (see Fig. 2b, c, shown by arrows 2), which are saturated with oxygen atoms to form oxide films and solid solutions of oxygen. The regions appear as early as after 10^4 loading cycles, and the area of the regions increases with the growth in the number of loading cycles up to 10^6. The fretting processes do not significantly influence the contact damage of the composite coating in the given loading conditions [5].



(a) (b) (c)

FIGURE 2. Influence of the number of loading cycles N on the contact spot diameter d (a) and SEM images of contact spots that were loaded with the number of cycles N = 10^4 (b) and N = 10^6 (c) after contact fatigue tests of the NiCrBSi–15%Cr_3C_2 coating

Figure 3 shows the dependences of the EC instrument readings on the number of loading cycles, which were measured on the contact spots after contact fatigue tests of the composite coating. It can be seen that for the NiCrBSi–15%Cr_3C_2 composite coating, these dependences have a qualitatively identical character for all excitation frequencies of the EC transducer. For this character, the EC instrument readings sharply decrease down to 10^4 loading cycles first, and then the value of α gradually decreases down to 3×10^5 loading cycles. As the number of contact loading cycles grows to 5×10^5, a considerable increase of the value of α is observed. The further loading is accompanied by a gradual increase of the EC instrument readings. As the excitation frequency of the EC transducer increases, the considered dependences become more pronounced. The differences of the dependences of the EC instrument readings α on the number of loading cycles in measurements at different excitation frequencies f of the EC transducer are determined by the different electromagnetic field penetration depths δ [5] (as f increases, δ decreases). The complex character of the EC instrument readings as a function of the number of loading cycles is determined by the combined actions of cracking, cohesive spalling and compaction of the composite coating. Cracking decreases the EC instrument readings due to an increase in the resistivity of the surface layer that contains cracks, while the latter increase the EC instrument readings due to a decrease in the coating resistivity. The formation of oxide films and solid solutions of oxygen on the coating surface does not significantly influences the results of the electromagnetic measurements [5]. Thus, the EC testing of the fatigue degradation under contact loading of the NiCrBSi–15%Cr_3C_2 composite coating can be performed at high excitation frequencies 72-120 kHz of the EC transducer, when a thin surface layer subjected to fatigue degradation is analyzed to a higher degree. At that, the dependences of the EC instrument readings on the number of loading cycles have both downward and upward branches, with the boundary between the branches being 3×10^5 cycles in the given loading conditions. The downward branch can be used to monitor the processes of crack formation and growth, the upward branch – to monitor the degree of cohesive spalling, while taking into account in the testing methodology an ambiguous character of the dependences of the EC instrument readings on the number of loading cycles.

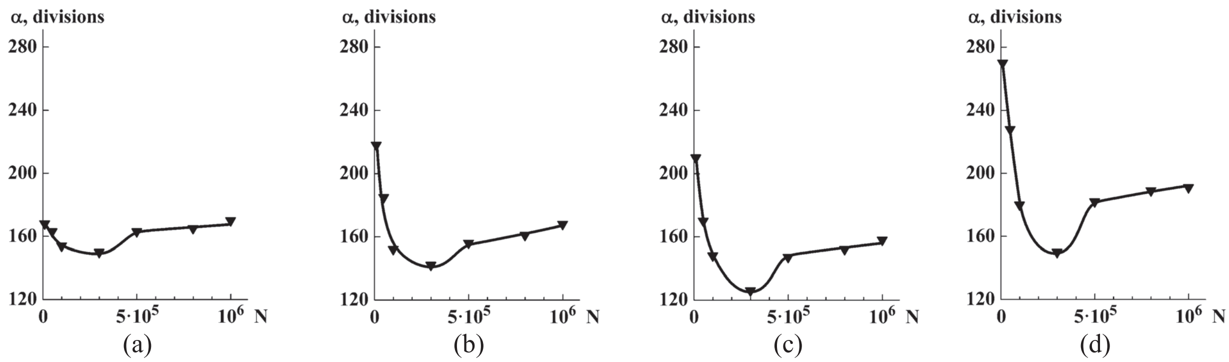


FIGURE 3. Influence of the number of loading cycles N on the EC instrument readings α measured at frequencies of 36 kHz (a), 72 kHz (b), 96 kHz (c) and 120 kHz (d) within contact spots after contact fatigue tests of the NiCrBSi–15%Cr_3C_2 coating

CONCLUSIONS

The possibilities of the eddy-current (EC) testing of the fatigue degradation under contact loading of gas powder laser clad NiCrBSi–Cr_3C_2 composite coating with 15 wt.% of Cr_3C_2 additive have been established. It is shown that the EC testing of the fatigue degradation under contact loading of the NiCrBSi–15%Cr_3C_2 composite coating can be performed at high excitation frequencies 72-120 kHz of the EC transducer. At that, the dependences of the EC instrument readings on the number of loading cycles have both downward and upward branches, with the boundary between the branches being 3×10^5 cycles in the given loading conditions. This is caused, on the one hand, by cracking, and, on the other hand, by cohesive spalling and compaction of the composite coating, which affect oppositely the material resistivity and, correspondingly, the EC instrument readings. The downward branch can be used to monitor the processes of crack formation and growth, the upward branch – to monitor the degree of cohesive spalling, while taking into account in the testing methodology an ambiguous character of the dependences of the EC instrument readings on the number of loading cycles.

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